REPORT PAPER - DRIVERS FOR BIODEGRADABLE/COMPOSTABLE PLASTICS AND ROLE OF COMPOSTING IN WASTE MANAGEMENT AND SUSTAINABLE AGRICULTURE

R. Narayan

Department of Chemical Engineering, Michigan State University, East Lansing, MI 48824 USA, http://www.msu.edu/user/narayan

1. ABSTRACT

Sustainability, industrial ecology, ecoefficiency, and green chemistry are the new principles that are guiding the development of the next generation of plastic and other products and processes. Thus, new products have to be designed and engineered from "conception to reincarnation" incorporating a holistic "life cycle thinking approach". The rationale and drivers for manufacturing eco-efficient, sustainable, and biodegradable/compostable plastics are discussed on the basis of global carbon cycling, design principles for the environment, and disposal/waste management infrastructures. Designing plastics, used in single-use disposable packaging and consumer goods, to be biodegradable and ensuring that they end up in composting systems is environmentally and ecologically sound. Composting as an ecologically important tool, not only for waste management but also for sustainable agriculture practices.

Biodegradable plastics and biobased products based on annually renewable agricultural and biomass feedstocks can form the basis for a portfolio of sustainable, ecoefficient products that can compete and capture markets currently dominated by products based exclusively on petroleum feedstocks. Biodegradable plastic products are under commercialization by several small and major companies. Worldwide Standards for biodegradable/compostable plastics and certification/logo schemes are in place

2. INTRODUCTION

New environmental regulations, societal concerns, and a growing environmental awareness throughout the world have triggered the search for new products and processes that are compatible with the environment. Sustainability, industrial ecology, ecoefficiency, and green chemistry are the new principles that are guiding the development of the next generation of products and processes. Thus, new products have to be designed and engineered from "conception to reincarnation" incorporating a holistic "life cycle thinking approach". The ecological impact of raw material resources used in the manufacture of a product and the ultimate fate (disposal) of the product when it enters the waste stream has to be factored into the design of the product. The use of annually renewable resources and the biodegradability or recyclability of the product is becoming an important design criterion. This has opened up new market opportunities for developing biodegradable and biobased products as the next generation of sustainable materials that meets ecological and economic requirements -- ecoefficient products (Narayan, 1991, 1992, 1994a, 1998).

Currently, most products are designed with limited consideration to its ecological footprint especially as it relates to its ultimate disposability. Of particular concern are plastics used in single-use disposable packaging and consumer goods. Designing these materials to be biodegradable and ensuring that they end up in an appropriate disposal system is environmentally and ecologically sound. For example, by composting our biodegradable plastic and paper waste along with other "organic" compostable materials like yard, food, and agricultural wastes, we can generate much-needed carbon-rich compost (humic material). Compost amended soil has beneficial effects by increasing soil organic carbon, increasing water and nutrient retention, reducing chemical inputs, and suppressing plant disease. Composting is increasingly a critical element for maintaining the sustainability of our agriculture system. The attached Figure 1 shows a conceptual schematic for the closed loop use of corn feedstock to prepare starch and protein, process them into biodegradable, single use, disposable packaging and plastic ware for use in fast-food restaurants. The food wastes along with other biowastes are separately collected and composted to generate good, valuable soil amendment that goes back on the farmland to re-initiate the carbon cycle (Narayan, 1993, 1994b)

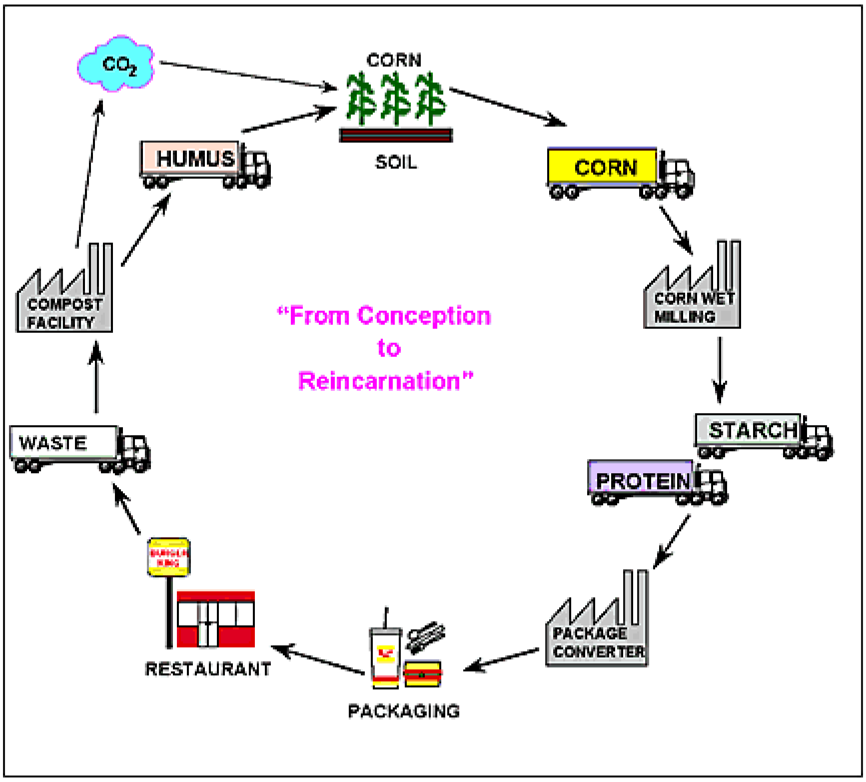


Figure 1. Closed loop use of corn feedstock

Polymer materials have been designed in the past to resist degradation. The challenge is to design polymers that have the necessary functionality during use, but destruct under the stimulus of an environmental trigger after use. The trigger could be microbial, hydrolytically or oxidatively susceptible linkage built into the backbone of the polymer, or additives that catalyze breakdown of the polymer chains in specific environments. More importantly, the breakdown products should not be toxic or persist in the environment, and should be completely utilized by soil microorganisms in a defined time frame. In order to ensure market acceptance of biodegradable products, the ultimate biodegradability of these materials in the appropriate waste management infrastructures in reasonable time frames needs to be demonstrated beyond doubt.

ASTM, European (CEN), German (DIN), Japan (JIS) and ISO (International Standards Organization) Standards have been developed or are under development to evaluate biodegradability under different environmental/disposal conditions like composting, soil, marine, wastewater treatment facility, and anaerobic digesters. ISO has also formed a technical committee (ISO/TC 207) to address standardization in the field of environmental management and brings to the forefront the need for industry to address how their products and processes impact the environment. It is expected that these Standards will have an impact on the industry similar to ISO 9000. These and other programs like "Responsible Care" will continue to drive industry towards sustainable, ecoefficient products like compostable/biodegradable plastics.

This paper:

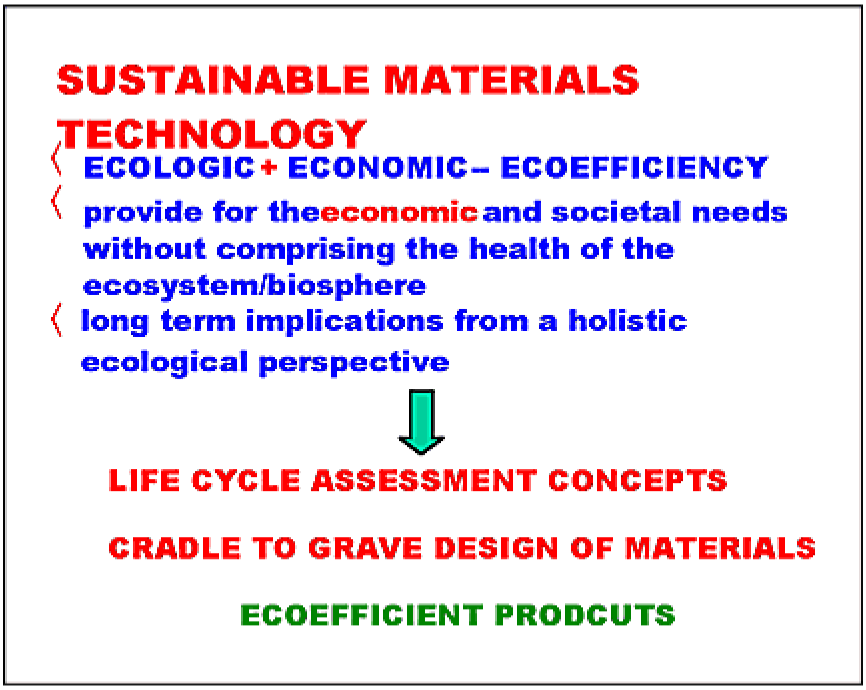
1. Discusses the rationale and drivers for manufacturing eco-efficient, sustainable, and biodegradable/compostable plastics.
2. Presents the importance of composting as an ecologically important tool, not only for waste management but also for sustainable agriculture.
3. Reviews the importance and current status of evolving worldwide Standards for biodegradable/compostable plastics.

4.

3. RATIONALE & DRIVERS FOR BIODEGRADABLE/COMPOSTABLE PLASTICS

3.1 Sustainability and Material Design for the Environment

The UN World Commission on Environment & Development in Our Common Future defines sustainability as "the development, which meets the needs of the present without compromising the ability of future generations to meet their own needs". However, in a free market economy, the economics of a product needs to be factored in to the sustainability equation — the design and engineering of ecoefficient products as illustrated in the attached Figure 2.



SUSTAINABLE MATERIALS TECHNOLOGY

- **ECOLOGIC + ECONOMIC – ECOEFFICIENCY**
- **provide for the economic and societal needs without comprising the health of the ecosystem/biosphere**
- **long term implications from a holistic ecological perspective**

LIFE CYCLE ASSESSMENT CONCEPTS

CRADLE TO GRAVE DESIGN OF MATERIALS

ECOEFFICIENT PRODCUTS

Figure 2. Sustainable materials technology

Manufacturers traditionally have not concerned themselves with the impact on the environment of using various feedstocks. They have also not worried about the ultimate disposability of their product. The products of the future must be designed from "conception to reincarnation" using holistic life cycle concepts. The use of annually renewable biomass, like corn, as opposed to petrochemicals (oil or natural gas) as the feedstocks for the production of polymers, chemicals, and fuel needs to be understood from a global carbon cycle basis. Clearly petrochemical feedstocks are also "natural". These fossil resources are formed from biomass over geological time frames. The problem is that the rate at which biomass is converted to fossil resources is in total imbalance with the rate at which they are consumed ($>10^5$ years vs. 1-10 years).

The use of annually renewable biomass to produce the polymer materials, chemicals, and fuel as an adjunct to fossil resources would begin to move the rate of CO2 fixation more in balance with the rate at which CO2 is released. Furthermore, if we manage our biomass resources effectively by making sure that we plant more biomass (trees, crops) than we utilize, we can begin to start reversing the CO2 rate equation and move towards a net balance between CO2 fixation/sequestration and release due to consumption. The attached Figure 3 illustrates these concepts for the global cycling of carbon, and demonstrates that the use of annually renewable biomass resources for the production of polymers, chemicals, and fuel contributes positively towards sustainability and global carbon recycling.

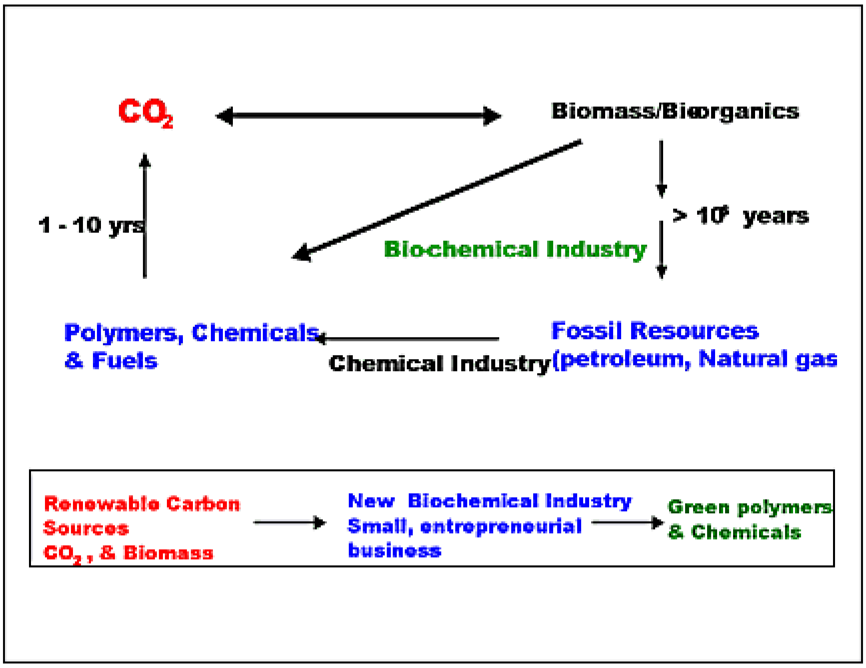


Figure 3. Global carbon cycling; the eco-driver

Given this importance of biobased products and fuel for sustainability and global CO_2 reductions, the US President through Executive Order 13101 (Greening the Government Through Waste Prevention, Recycling, and Federal Acquisition, dated September 14, 1998) has asked Federal Government agencies to procure biobased products. Biobased product is defined as a commercial or industrial product (other than food or feed) that utilizes biological products or renewable domestic agricultural (plant, animal, and marine) or forestry materials. U.S. Department of Agriculture (USDA) is proposing guidelines for listing commercially available biobased products for purchase by Federal agencies. USDA is listing only those products, which are considered by USDA to be within the U.S. Environmental Protection Agency (EPA) Environmentally Preferable Products Guidelines.

Thus, one can enunciate the principles of "materials design for the environment". It involves paying attention to the feedstock used, and as discussed earlier the use of biomass feedstock would be preferable if the final product can meet cost-performance specifications and not contribute to any other additional environmental burdens in the process — Life Cycle Thinking Concepts. The material design principles for the environment also require that one address the issue of what happens to the material/product after use by customer when it enters the waste stream. — the ultimate disposability of the product. The goal in this step is to transform the waste into a useful product. Figure 4 captures the elements of the material design principles for the environment.

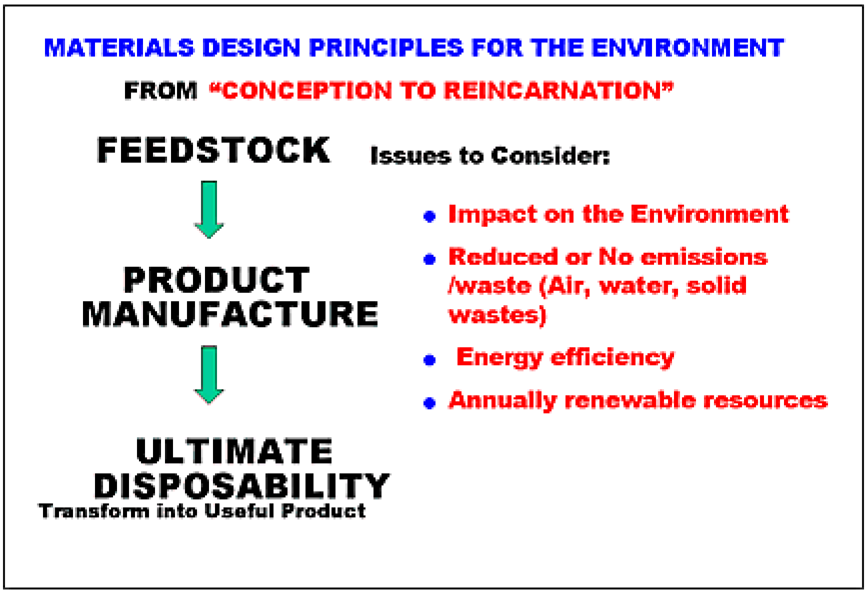


Figure 4. Design, use, disposal, and reuse of materials incorporating life thinking

3.2 Integration of Product Design with Disposal Infrastructure

As discussed above the ultimate disposal of materials in an ecologically sound manner has become an important factor in the design of the material. Making or calling a product biodegradable or recyclable has no meaning whatsoever if the product after use by the customer does not end up in a disposal infrastructure that utilizes the biodegradability or recyclability features. Recycling makes sense if the recyclable product can be easily collected and sent to a recycling facility to be transformed into the same or new product. Biodegradable products would make sense if the product after use ends up in a disposal infrastructure that utilizes biodegradation. Composting, waste water/sewage treatment facilities, and managed, biologically active landfills (methane/landfill gas for energy) are established biodegradation infrastructures Therefore, producing biodegradable plastics and products using annually renewable biomass feedstocks that generally end up in biodegradation infrastructures like composting is ecologically sound and promotes sustainability. Materials that cannot be recycled or biodegraded can be incinerated with recovery of energy (waste to energy). Landfills are a poor choice as a repository of plastic and organic waste. Today's sanitary landfills are plastic-lined tombs that retard biodegradation because of little or no moisture and negligible microbial activity. Organic waste such as lawn and yard waste, paper, food, biodegradable plastics, and other inert materials should not be entombed in such landfills. Figure 5 illustrates the cradle to grave material design concepts.

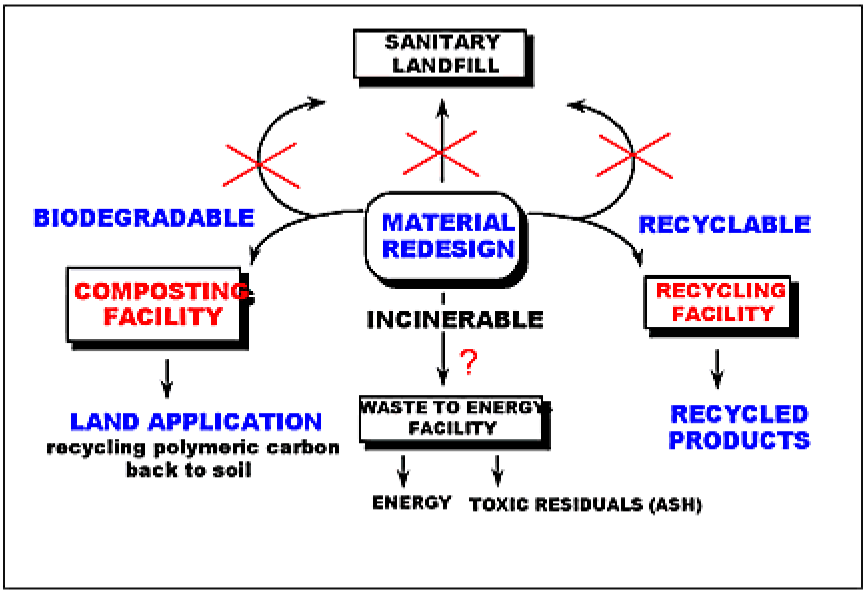


Figure 5. Cradle-to-grave concept for material design

Composting is an environmentally sound approach to transfer biodegradable waste, including the new biodegradable plastics, into useful soil amendment products. Composting is the accelerated degradation of heterogeneous organic matter by a mixed microbial population in a moist, warm, aerobic environment under controlled conditions.

Biodegradation of such natural materials will produce valuable compost as the major product, along with water and carbon dioxide. The CO_2 produced does not contribute to an increase in greenhouse gases because it is already part of the biological carbon cycle. Composting our biowastes not only provides ecologically sound waste disposal but also provides much needed compost to maintain the productivity of our soil and sustainable agriculture. (Narayan, 1989, 1993a, 1994b)

4. COMPOSTING & SUSTAINABLE AGRICULTURE

Soil erosion is a major, worldwide environmental and agricultural problem. Although erosion has occurred throughout the history of agriculture, it has intensified in recent years. Each year, 75 billion metric tons of soil is removed from the land by wind and water erosion. Most is removed from agricultural land. The use of large amounts of fertilizers, pesticides, and irrigation help offset deleterious effects of erosion but also has the potential to create pollution and health problems, destroy natural habitats, and contribute to high-energy consumption and unsustainable agricultural systems. Erosion is also a major cause of deforestation: since more forests are cut and converted to agricultural production when existing plots become degraded.

Crop yields on severely eroded soil are lower than those on protected soils because erosion reduces soil fertility and water availability. Corn yields on some severely eroded soils have been reduced by 12 to 21% in Kentucky, 0 to 24% in Illinois and Indiana, 25 to 65% in the southern Piedmont (Georgia), and 21% in Michigan. All crops require enormous quantities of water for their growth and the production of fruit. For example, during a single growing season, a hectare of corn (yield, 7000 kg ha^{-1}) transpires about 4×10^6 liters of water, and an additional 2×10^6 liters ha^{-1} concurrently evaporates from the soil.

Organic matter, a necessary component of soil, facilitates the formation of soil aggregates, increases soil porosity, and thereby improves soil structure, and ultimately overall productivity. In addition, organic matter increases water infiltration, facilitates cation exchange, enhances root growth, and stimulates the proliferation of important soil biota. About 95% of the nitrogen and 25 to 50% of the phosphorous in topsoil is contained in organic matter.

Once the organic matter layer is depleted, soil productivity and crop yields decline because of the degraded soil structure and lost availability of nutrients. For example, the reduction of soil organic matter from 4.3 to 1.7% lowered the yield potential for corn by 25% in Michigan. The erosion typical of conventional agriculture may decrease the diversity and abundance of soil organisms, whereas practices that maintain or add (as in compost addition) soil organic matter content at optimum levels favor the proliferation of soil biota. The application of organic matter may increase earthworm and microorganism biomass as much as fivefold. Soils form slowly: It takes between 200 and 1000 years to form 2.5 cm (1 inch) of topsoil under cropland conditions, and even longer under pasture and forest conditions.

In the United States, an estimated 4×10^9 tons of soil and 130×10^9 tons of water are lost from the 160×10^6 ha of cropland each year. This translates into an on-site economic loss of more than $27 billion each year, of which $20 billion is for replacement of nutrients and $7 billion for lost water and soil depth. When economic costs of soil loss and degradation and off-site effects are conservatively estimated into the cost/benefit analyses of agriculture, it makes sound economic sense to invest in programs that are effective in reducing widespread erosion.

Compost can provide the much-needed organic matter in soil, and in combination with conventional soil conservation methods, provide an answer to the major environmental and agricultural problem of soil erosion. The benefits of compost-amended soil include:

- increasing organic carbon,
- improving water and nutrient retention,
- reducing the need for additional chemical inputs,
- favoring the proliferation of soil biota, and
- suppressing plant disease.
- increase earthworm and microorganism biomass as much as fivefold

The feedstock for producing compost is biowastes -- produce and grocery, food wastes, agricultural, lawn, yard, and paper wastes. Approximately 50% of landfill trash is composed of paper, organic, and food wastes, all of which are partially or fully biodegradable. Thus, composting our biowastes (food, leaves, grass, wood, agricultural) along with new biodegradable plastic packaging and paper waste not only solves the problem of ecologically sound waste disposal but, provides much needed compost to maintain the productivity of our soil and support sustainable agriculture.

Biodegradable plastics and biobased products based on annually renewable agricultural and biomass feedstocks can form the basis for a portfolio of sustainable, ecoefficient products that can compete and capture markets currently dominated by products based exclusively on petroleum feedstocks. Biodegradable plastic products are under commercialization by several small and major companies. The technologies are based on aliphatic polyesters and copolyesters, microbial polyesters, thermoplastic starch and starch derivatives, proteins, and blends of these with the biodegradable synthetic polyesters. (Narayan 1992, 1993b, 1994a, 1998).

5. STANDARDS FOR BIODEGRADABLE PLASTICS (Narayan, 1999, 1994b)

When industry began implementing approaches to design biodegradable plastics and products, questions about the practicality, efficacy, and the effects of such products on the environment were raised. The U.S. Federal Trade Commission (FTC), a group of State Attorney General's, State legislatures, and the U.S. Congress became very concerned about the various degradability and environmental claims being made, especially as they related to existing waste management practices. Verification of degradability claims and environmental fate and effects of the new degradable products using acceptable well-defined testing protocols were lacking.

The plastics industry failed to take advantage of this opportunity at the beginning by introducing starch filled (6-15%) polyolefins that were claimed to be biodegradable materials. At best, these materials only disintegrated and did not completely biodegrade. The introduction of these materials resulted in a number of regulatory actions. Eleven States enacted environmental marketing claim laws. A task force of several State Attorney Generals' issued recommendations

(Green Report I & II) on advertising related to products and environmental attributes. Between October 1990 and June 1992, 48 separate actions were taken for misleading or deceitful environmental advertising, the highest number of actions were on claims of biodegradable plastics, and the use of the terms biodegradable and recyclable.

Thus, it became increasingly clear that Standards were sorely needed in this arena. Standard test methods and protocols were needed to establish and quantify the degradability and biodegradability of polymers, and to confirm the benign nature of the breakdown products. In order to ensure societal, regulatory, and market acceptance of biodegradable plastics, the ultimate biodegradability of these materials needed to be demonstrated in appropriate waste management infrastructures (like composting where biodegradation can occur).

Standards have been developed or are under development by National Standards bodies (USA (ASTM); European (CEN), German (DIN), Japan (JIS)) and the International Standards Organization (ISO) to evaluate and quantify biodegradability under different environmental/disposal conditions like composting, soil, marine, wastewater treatment facility, and anaerobic digesters. The Standards are in harmony with each other and there are no major differences between them. It is expected that the ISO Standards will bring all these Standards together and provide globally acceptable Standards. Certification and logo schemes based on these Standards are in place.

5.1. ASTM (USA)

ASTM Technical Committee on Plastics (D20) formed a subcommittee D20.96 on "Environmentally Degradable Plastics" to address the issue of standards for degradable polymers. The scope of the subcommittee was the promotion of knowledge, and the development of standards (classification, guide, practice, test method, terminology, and specification) for plastics, which are intended to environmentally degrade. One hundred and seventy plus members representing a broad spectrum of interests ranging from producers, converters, users, consumers, and general interest joined the subcommittee. Industry, government, academia, and national laboratories were represented on the subcommittee.

A major milestone was met with the approval of the "Standard Specification for Compostable Plastics" D6400-99 (ASTM, 1999). This Standard establishes criteria (specifications) for plastics and products made from plastics to be labeled compostable. It establishes whether plastics and products made from plastics will compost satisfactorily, including biodegrading at a rate comparable to known compostable materials. This specification is comparable to what is being developed by CEN (European Committee for Standardization) in Europe today, and in harmony with the German Standard (DIN 54900), moving the industry closer to global standards. The Specification Standard is based on and references three other D20.96 Standard documents for the testing and identification of plastics that will biodegrade and compost satisfactorily. They are (ASTM, 1999):

1. D 6002-96 Standard Guide for Assessing the Compostability of Environmentally Degradable Plastics–outlines recommended procedures, and a general approach to establish the compostability of plastics. It provides a three-tiered criteria-based approach, which includes rapid screening tests, laboratory and pilot scale composting assessment, and field/full scale assessment.
2. D 5338-98 Standard Test Method for Determining Aerobic Biodegradation of Plastic Materials Under Controlled Composting Conditions–determines the degree and rate of aerobic biodegradation of plastic materials on exposure to a controlled-composting environment under laboratory conditions
3. D6340-98 Standard Test Method for Determining Aerobic Biodegradation of Radiolabeled Plastic Materials in an Aqueous or Compost Environment–determines the rate and degree of biological oxidation of carbon in plastic materials when placed in a composting environment containing simulated municipal solid waste or an aqueous environment under laboratory conditions. It applies to plastics whose biodegradation rate is slow and requires test periods for as long as 365 days.

The U.S. Composting Council jointly with the International Biodegradables Products Institute (www.bpiworld.org) has instituted a certification scheme for compostable plastics that is based on the ASTM D6400 Specification Standard. Products meeting the Standard, as verified by the Scientific Review Committee, can carry the Compostable logo of the U.S. Composting Council-Biodegradables Products Institute. Discussions are underway to harmonize certification schemes between the U.S., German (DIN-CERTCO), Belgium (OK Compost), and Japan programs.

5.2 European Standards (CEN, DIN)

The European Commission (EC) has mandated the development of Standards for Biodegradable Packaging Materials. This is under the jurisdiction of CEN TC 261(packaging)/SC4 (packaging & environment)/WG2(degradability & compostability). The Standard (EN 13432) is very similar to the ASTM D6002, except that it has pass/fail specifications built into it. The key specification is the requirement of >90% biodegradability for blends, copolymers etc., as measured by ISO14855 (controlled composting) test method.

In Germany for biodegradable plastics to be accepted in compost operations and satisfy the DSD requirement, the plastic will have to pass the DIN 54900 (DIN, 1998). This is similar to the CEN standard and is a three tiered testing protocol (like the ASTM D6002). It has the same strict pass/fail requirements of the CEN Standard — requiring complete biodegradability and disintegration to become a integral part of the compost. A product certification from DIN-CERTO (an affiliate of the DIN Standards Organization) would be needed — third part validation.

5.3 International Standards Organization (ISO) Standards

ISO/TC 61 is the International Committee responsible for Plastics standards. Under this committee biodegradable plastic International Standards are in development in Subcommittee 5, Working Group 22. These Standards are in harmony with the ASTM, CEN (European), and DIN (German) Standards. Several Standards have issues and more are under development. The issued Standards are (ISO, 1999):

1. ISO14851 Determination of the ultimate aerobic biodegradability of plastics materials in an aqueous medium - Method by measuring the oxygen demand in a closed respirometer.
2. ISO14852 Determination of the ultimate aerobic biodegradability of plastics materials in an aqueous medium - Method by analysis of evolved carbon dioxide
3. ISO14855 Determination of the ultimate aerobic biodegradability and disintegration of plastic materials under controlled composting conditions - Method by analysis of evolved carbon dioxide

Several other Standards are close to being issued. These are:

- Standards for disintegration of plastics under defined composting conditions in a pilot-scale test (ISO/DIS16929)
- Aerobic biodegradability in soil (ISO/DIS17556)
- Ultimate anaerobic biodegradability in digester (ISO/FDIS14853) and high solids digester (ISO/FDIS15985)
- Test scheme & specifications for compostable plastics (ISO/CD 17088)

6. ACKNOWLEDGEMENTS

A version of this paper has been published in the Proceedings of an "ORBIT Special Event" on Biodegradable Polymers: production, marketing, utilisation, and residue management (ISBN 3-86068-143-5).

LIST OF REFERENCES

- ASTM (1999). *ASTM Book of Standards*. Plastics (III), Volume 08.03, July 2000.
- DIN (1998). DIN (Deutsches Institut fur Normung)54900. Standard for testing the compostability of polymeric materials
- ISO (1999). International Standards Organization, ISO Standards from TC 61 on Plastics, 83.080.01 Plastics in general
- Narayan R., Pettigrew C. (1999). *ASTM Standardization News*, December 1999 (downloadable from http://www.astm.org/; technical committee, D20.96 as a PDF file)
- Narayan R. (1998). Commercialization Technology: "A Case Study of Starch Based Biodegradable Plastics" In: *Paradigm for Successful Utilization of Renewable Resources*, D.J. Sessa and J.L. Willett (Eds.), AOCS Press, Champaign, Illinois, pp. 78
- Narayan R. (1994). Polymeric Materials from Agricultural Feedstocks, In*: Polymers from Agricultural Coproducts*, M.L. Fishman, R.B. Friedman, and S.J. Huang (Eds.), *American Chemical Society Symposium Series*, 575, 2.

- Narayan R. (1994). Impact of Governmental Policies, Regulations, and Standards Activities on an Emerging Biodegradable Plastics Industry, In: *Biodegradable Plastics and Polymers*, Y. Doi & K. Fukuda (Eds.), Elsevier, New York, pp. 261.
- Narayan R. (1993). Biodegradation of Polymeric Materials (Anthropogenic Macromolecules) During Composting, In: *Science and Engineering of Composting: Design, Environmental, Microbiological and Utilization Aspects;* H. A. J. Hoitink and H.M. Keener (Eds.), Renaissance Publications, Ohio, pp. 339.
- Narayan R. (1993) Biodegradable Plastics, In: *Opportunities for Innovation: Biotechnology*, National Institute of Standards and Technology (NIST, U.S. Department of Commerce) Monograph; NIST GCR-93-633, pp. 135.
- Narayan R. (1992). Biomass (Renewable) Resources for Production of Materials, Chemicals, and Fuels -- A Paradigm Shift, *American Chemical Society Symposium Series*, 476, 1.
- Narayan R. (1991) Rationale and Design of Environmentally Degradable Nonwovens. *INDA Nonwovens Res*., 3, 1.
- Narayan R. (1989). Environmentally Degradable Plastics, *Kunststoffe*, 79 (10), 1022.